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Development of intermediate cooling technology and its control for two-stand plate rolling

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Abstract

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Keywords

plate, two-stand, control, development, its, rolling, technology, cooling, intermediate

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Research Article

Development of Intermediate Cooling Technology and Its Control for Two-Stand Plate Rolling

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In a plate rolling production line, thermomechanically controlled processing is critical for plate quality. In this paper, a set of intermediate cooling equipment of a two-stand plate mill with super density nozzles, medium pressure, and small flow is developed. Based on a simplified dynamic model, a cooling control scheme with combined feedforward, feedback, and adaptive algorithms is put forward. The new controlled rolling process and the highly efficient control system improve the controlled rolling efficiency by an average of 17.66%. The proposed intermediate cooling system can also effectively inhibit the growth of austenite grain, improve the impact toughness and yield strength of Q345B steel plate, reduce the formation of secondary oxide scale on the plate surface and the chromatic aberration of the plate surface, and greatly improve the surface quality of the steel plate.

1. Introduction

Thermomechanical control processing (TMCP) is a microstructural control technique combining controlled rolling and controlled cooling. The mechanical properties introduced to the steel through TMCP route are virtually equivalent to those obtained by heat treating conventionally rolled or forged steel. It can be optimized by control of phase transformation of austenite with cooling technology during or after hot rolling process [1, 2]. By appropriate choice of deformation temperature and strain rate, the strength of steel can be increased. The strength of TMCP steel is higher than of normalized steel of the same composition [3, 4]. Thus, TMCP steel has a leaner composition (lower alloy content) than conventional normalized steel of the same strength.

Controlled rolling and controlled cooling technology is widely used in medium and heavy plate production and plays an important role in the performance of the products on the side. But, during controlled rolling process, the rolling in the temperature range of partial recrystallization region between the recrystallization and nonrecrystallization zone must be stopped for temperature holding to avoid the appearance of mixed grain structure which will affect the quality of the products. Generally, the temperature holding process is completed by air cooling of swinging intermediate slab on roller table [5]. The cooling process of slab in the air is a relatively slow process of temperature drop, which affects the production efficiency. The production capacity of plate mill using controlled rolling generally decreases by 26–30%. Therefore, improving the cooling efficiency and reducing the holding time are an important means to improve the production efficiency and comprehensive properties of the plate [6, 7]. One of the effective ways is the water cooling in rolling process, namely, the intermediate cooling (IC) process.

IC technology is to install cooling equipment between the roughing mill (RM) and the finishing mill (FM) of a two-stand plate production line to reduce holding time and increase production capacity. Research shows that the water cooling of intermediate slab in temperature holding process can reduce holding time and improve the rolling efficiency under the premise that no mechanical properties of the products would be reduced [8–11]. But, before finishing rolling, the rereddening process of intermediate slab should be finished

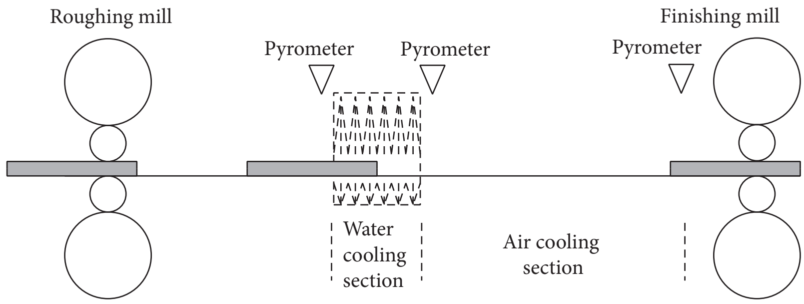


Figure 1: Schematic layout of the production line.

after water cooling to reduce the temperature gradient along thickness direction and avoid affecting the rolling process [12]. Experiments have proved that the temperature drop of intermediate slab by water cooling during controlled rolling can reduce 15–20% of the holding time and improve the rolling efficiency to a certain degree [13]. Combined with the actual situation of a plate mill with a roll width of 3000 mm, we designed the water cooling equipment before the finishing mill for rapidly reducing temperature of intermediate slab to control finishing rolling temperature, as shown in Figure 1.

Figure 2: Working intermediate cooling equipment.

2. Overview of Intermediate Cooling

2.1. Rolling Force Model. The IC section is located between the RM and the FM, and the main components include six groups of 650 mm spacing coolers. Basic parameters of the IC technology and equipment are as follows.

The thickness and width range of intermediate slab are 40–110 mm and 1600–2850 mm, respectively; the starting temperature, the ending temperature, and the rereddening temperature of intermediate slabs are separately 1050–1030°C, below 950°C, and 880–950°C; the roller spacing of roller table is 650 mm; the length of cooling zone is 3.9 m; the length of the longest intermediate slabs is 12 m; the pressure of cooling water is 0.4 MPa; the distance between the centerline of RM and the centerline of finishing mill is 78 m, and the distance between the centerline of RM and the centerline of the first group of coolers is 26.345 m; the cooling mode is multipurpose interrupt cooling (MULPIC) of one pass or swing; the cooling water is turbid circulating water. Cooling product mainly includes high-strength low-alloy intermediate slabs such as shipbuilding plate and structural plate.

2.2. Equipment. IC equipment comprises filtration system, water supply pipe, flow regulation device, spraying and cooling device, measuring instruments, and automatic control system. The working IC equipment is shown in Figure 2.

Mechanical system is the main equipment of accelerated cooling after rolling system and is the basis of accelerated cooling. The mechanical system primarily consists of the following subsystems: water supply and water recycling system, water distribution system, high-density laminar system, edge masking system, side spray system, and front and rear blowing system. The main part of the water supply system is the pumping system, whose task is to provide cooling water to meet the requirements of the temperature and flow for the cooling system when the plate is cooled and which consists of a number of variable frequency drive pumps and high pressure pumps for water supply. Cooling water circulation system mainly consists of outside plant cooling towers, cooling ponds, and other components.

Medium pressure water passes through the water tank in the workshop after being filtered and then is assigned to every cooler. Water out of the coolers directly passes through the trench of the IC section and then returns to the water treatment system. Water distribution system consists of the medium level water tank and the water distributor in the workshop. The medium level water tank has steady flow, water buffer, and exhaust function. The main function of the water distributor is to evenly distribute the water in the medium level water tank to each cooler, so as to realize the uniform cooling of the steel plate. The side masking system can automatically adjust the horizontal water spraying of the cooling manifold according to the different widths of the steel plate to improve the control precision of the horizontal temperature of the steel plate.

The side masking system can improve the cooling efficiency and capacity of cooling water and improve the cooling uniformity of steel plate. The blowing system can guarantee plate surface cleaning when the plate enters and leaves the cooling zone, improve the surface quality of steel plate, and improve the detection accuracy of the plate temperature.

2.3. Technological Process. The most basic type of IC includes recrystallization type controlled rolling, unrecrystallization type control rolling, and (α + β) two-phase region type controlled rolling. In the actual production process, engineers generally take the combination of the above two or three basic types of controlled rolling based on the rolling equipment capacity, the product performance requirements, and the cost-benefit analysis. Adopting TMCP mode from the high temperature recrystallization type controlled rolling to unrecrystallization type controlled rolling or ($\alpha + \beta$) two-phase region type controlled rolling, on the one hand, can avoid rolling in the austenite recrystallization zone and prevent the mixed crystal austenite and, on the other hand, can change the traditional air-cooled temperature holding and reduce holding time and, in addition, can relieve the production capacity pressure caused by the short distance of roller table between the RM and the FM.

The technological process is briefly described as follows.

Step 1. The intermediate slab enters the controlled cooling zone after roughing rolling.

Step 2. Determine the cooling scheme according to the measured temperature and the calculated thickness of the intermediate slab.

Step 3. When the intermediate slab enters the cooling zone, the front blowing system is turned on to prevent the cooling water from returning along the slab surface and affecting the normal work of measurement instruments and sensors when intermediate slab is being cooled in the controlled cooling zone.

Step 4. The corresponding cooling manifolds are opened according to the cooling scheme.

Step 5. After the intermediate slab has left the cooling zone, the rear blowing system promptly blows away the residual water on the slab surface to prevent the warping head phenomenon of the slab caused by uneven cooling of the upper and lower surface of the slab during finishing rolling process.

Step 6. After the intermediate slab has left the cooling zone, the rereddening is implemented to achieve uniform temperature of the intermediate slab, so as to prevent the nonuniform microstructure defects.

3. Temperature Model and Control Scheme

3.1. Rolling Force Model. The moving steel plate can be considered as a mass flow that is conveyed along the cooling roller table from the entry (roughing rolling) to the exit (finishing rolling). Over this period of time, the steel plate exchanges energy with the environment by convection and radiation.

The entry and exit locations of a slab are defined as the geometrical boundary of the dynamic model of the cooling process. Pyrometers are installed at the entry and exit locations to provide temperature measurements. The whole cooling section is divided into Q subcooling zones, and each intermediate slab is divided into n segments. Each segment of the plate is tracked by the controller in real time.

The surface temperature profile T of a plate in the cooling section can be described as a function of run-out time z [14]:

$$T = U_w + (T_e - U_w) \cdot e^{-Pz}, \qquad (1)$$

where U_w and T_e represent environment temperature and entry temperature, respectively. And P is a model coefficient, which is determined by the plate thickness, entry speed, heat transfer, and conduction of the plate. The value of P can be calculated as [14]

$$P = \frac{b_1}{(1/(a_1 + a_2)\,F + h/k_1 b_2)\,b_2 h k_2}, \qquad (2)$$

where b_1 is the thermal conduction coefficient and b_2 is the heat conduction coefficient. They are determined by empirical curves. The empirical parameters k_1 and k_2 are constant, and h is the thickness of the plate. The heat exchange coefficients a_1 and a_2 are for the upper and lower surface of the slab, respectively. These two factors are estimated with adaptive genetic algorithm. F is a coefficient depending on water tank pressure, water temperature, and plate speed. Its value is determined using experimental data for specific plant and operation conditions.

3.2. Feedforward Control Algorithm. There are typically 12 electric flow control valves and 12 pneumatic valves in the cooling section, located in a number of cooling zones. The cooling zones and the valves in each zone are coded in a systematic sequence in preparation for control.

Feedforward control is activated as soon as a plate enters the cooling section. The plate is divided into segments according to sampling time. As the sampling time is fixed, the length of each segment may vary with the plate speed. Based on model (1), the exit temperature of each segment can be predicted by the following formula in discrete form:

$$\begin{aligned} T(m,n) &= U_w + (T_e(m,n) - U_w) \cdot \exp(-P_{m,n} z_{m,n}), \\ P_{m,n} z_{m,n} &= \sum_{i=m}^{Q} P(i,n)\, z(i,n), \end{aligned} \qquad (3)$$

where Q is the total number of cooling zones. For the nth slab segment entering the mth subcooling zone, the environment temperature U_w and the entry temperature $T_e(m,n)$ are available from the sensors. The value of P is calculated using (2).

For a given reference exit temperature T_r, the objective of the feedforward control is to minimize the difference d between the predicted exit temperature $T_h(Q,n)$ and T_r:

$$d = |T_h(Q,n) - T_r|. \qquad (4)$$

If T_S is set to an expected exit temperature function and $T_S(Q,n)$ is equal to T_r, the control change can be determined by the following conversion:

$$\begin{aligned} T_h(m,n) &= U_w + \left(T_e(m,n) - U_w\right) \\ &\quad \cdot \exp\left[-\sum_{i=m}^{Q} P(i,n)\, z(i,n)\right], \\ T_S(m,n) &= U_w + \left(T_e(m,n) - U_w\right) \\ &\quad \cdot \exp\left[-\sum_{i=m}^{Q} P(i,n)\, z_S(i,n)\right], \end{aligned} \tag{5}$$

where z_S is the run-out time that is determined such that $T_S(Q,n)$ is equal to T_r. From (5),

$$\frac{T_h - U_w}{T_e - U_w} = \exp\left[-\sum_{i=m}^{Q} P(i,n)\, z(i,n)\right], \tag{6}$$

$$\frac{T_S - U_w}{T_e - U_w} = \exp\left[-\sum_{i=m}^{Q} P(i,n)\, z_S(i,n)\right]. \tag{7}$$

Combining (6) with (7) yields

$$\ln \frac{T_h - U_w}{T_S - U_w} = \left|P_{m,n} z_{m,n} - P_{m,n} z_{Sm,n}\right|. \tag{8}$$

The change of run-out time is calculated as follows:

$$\Delta z = \left|z_{m,n} - z_{Sm,n}\right| = \frac{\ln\left(\left(T_h - U_w\right)/\left(T_S - U_w\right)\right)}{P_{m,n}}. \tag{9}$$

It is assumed that the slab speed v is constant within a cooling zone, and the change in the activated cooling length of the cooling zone corresponding to the segment is determined as

$$\Delta L = v \cdot \Delta z = \frac{v \cdot \ln\left(\left(T_h - U_w\right)/\left(T_S - U_w\right)\right)}{P_{m,n}}. \tag{10}$$

The change in cooling length is implemented by adjusting the number and the flow of open cooling valves as the distance between valves is fixed.

3.3. Feedback Control Algorithm. As soon as the first segment enters the finishing rolling zone, its temperature is measured to start the feedback control. The measured temperature values replace the corresponding predicted values in the feedforward control.

For a measured cooling temperature function T_w, the change of the cooling length ΔL_f can be obtained as follows:

$$\Delta L_f(m,n) = \frac{v \cdot \ln\left(\left(T_w - U_w\right)/\left(T_S - U_w\right)\right)}{P_{m,n}}. \tag{11}$$

3.4. Adaptive Control Algorithm. In order to further improve the control accuracy with the measured cooling temperature, a correction factor K is introduced to fine-tune the value of P in model (3) as follows:

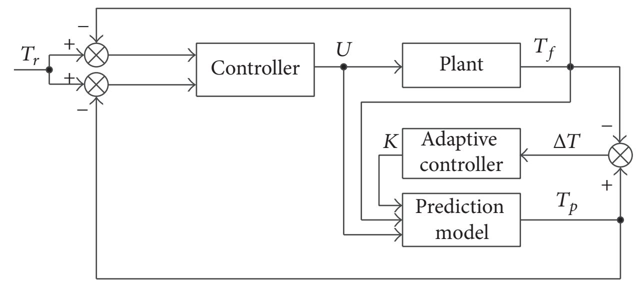


Figure 3: Block diagram of adaptive control scheme.

$$\begin{aligned} T_w(m,n) &= T_u + \left(T_e(m,n) - T_u\right) \\ &\quad \cdot \exp\left[-\sum_{i=m}^{Q} K(i,n)\, P(i,n)\, z(i,n)\right]. \end{aligned} \tag{12}$$

$K(m,n)$ is determined using the exit temperature measurements according to the following adaptive rule:

$$K(m,n) = K(m,n-l) + K_f\left[K_u - K(m,n-l)\right], \tag{13}$$

where K_f is a filter coefficient and K_u is determined by

$$\begin{aligned} K(m,n-l) &= \frac{1}{P(m,n-l)\, z(m,n-l)} \\ &\quad \cdot \ln \frac{T_w(m,n-l) - U_w(m,n-l)}{T_S(m,n-l) - U_w(m,n-l)}. \end{aligned} \tag{14}$$

The initial value of $K(m,n)$ for the first plate segment has to be assigned by experience using previous data.

The control scheme is illustrated in Figure 3, where T_r is the reference temperature, T_f is the feedback temperature, T_p is the predicted temperature, and U is the control value.

4. Intermediate Cooling Control System

4.1. System Structure. The control system structure is designed as three levels. Level 0 is the field device level, which mainly includes sensors, valves, and A-C and D-C digital drives. Level 1 (L1) is the basic automation level which consists of programmable logic controllers (PLCs) and microcomputers that manage the functional logic of the system, the single device control, and the interface with the sensors. Level 2 (L2), also known as the process automation level, consists of minicomputers that handle technological process and production targets and provide the user with tools for plant supervision and diagnostics. The applied automation control system designed for the intermediate control is shown in Figure 4.

4.2. Process Automation Level (L2). Process automation level, mainly referring to the process computers and corresponding application programs, is responsible for setting calculation of

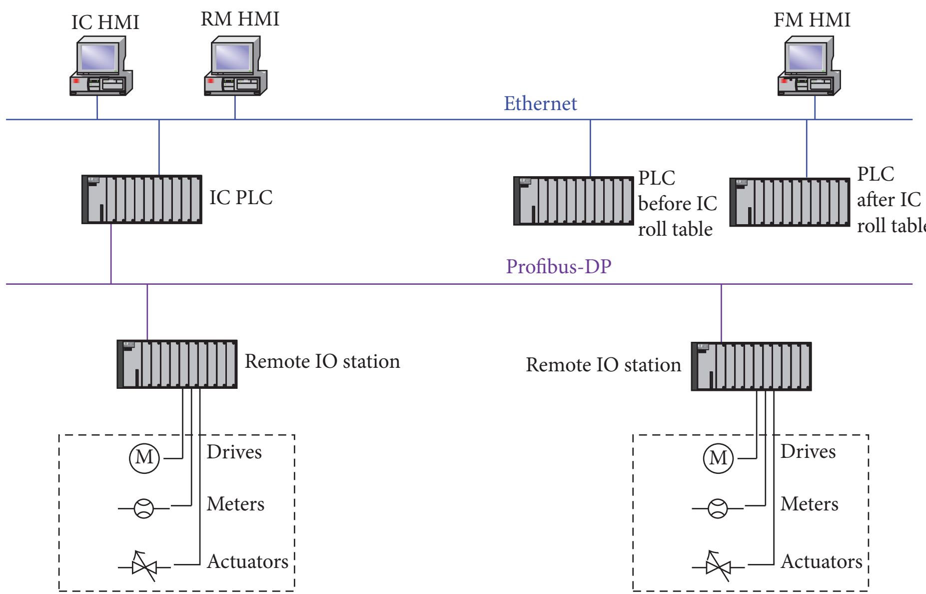


FIGURE 4: Block diagram of adaptive control scheme.

process model, sending set value (opening mode, steel plate by the speed of cooling zone, and the regulating value of the valve) to L1, and realizing the human-machine interface (HMI) between L1 and L2. The communication between L2 computers or with other devices is via Ethernet.

L2 workflow is described as follows: in the roll bite of last roughing pass, HMI computer delivers PDI parameters like size, grade, and finishing temperature to L2 computer, which calculates the preset values and sends the results to the PLC; when the head of intermediate slab reaches the entrance pyrometer, L2 computer calculates dynamic setting based on starting temperature and then sends the regulated signal to the PLC; when intermediate slab passes through the exit pyrometer, L2 computer records the cooling flow, slab speed, opening mode, ending temperature, rereddening temperature, and so forth, for model self-learning of the next intermediate slab of the same specification.

4.3. Process Automation Level (L2). L1 uses Siemens PLC S7-300 as the master control station and Siemens ET200 as remote IO station. L1 functions are as follows:

(1) *The Head and Tail Tracking Control.* PLC calculates the position of intermediate slab according to signal of the HMDs and other sensors.

(2) *Speed Control of Roller Table and Swing Control of Intermediate Slab Based on L2 Setup.*

(3) *Flow Control of the Cooler.* The function module regulates the opening position of the corresponding electric control valve to control the water flow of the cooler and open or close each group of manifolds according to the model setup and tracking results.

(4) *Signal Measurement and Collection.* PLC collects the signal from the sensors for validity check and process control.

(5) *Communication with the Process Control Computers.* PLC receives commands from L2 and transmits the collected signals to L2.

4.4. Human-Machine Interface (HMI). HMI system is an important component of the IC control system as well as the window of human-machine interaction. The function of the control system is divided into manual, semiautomatic, and automatic modes which are selected by the operator. The operator sends command to the control system via HMI and, at the same time, monitors the running state of the system. HMI system mainly completes the task of process monitoring, display, report output, online parameter settings (the speed parameters, the edge masking length of the slab head and tail, the number of the nozzle groups, the flow of the spay nozzles, etc.), model correction, fault alarm, trend recording, pump station remote monitoring, and so on. The home screen is shown in Figure 5.

5. Application Effect

5.1. Production Efficiency Improvement. According to the holding time of AC, the delivery time, the rolling time, and the number of intermediate slabs, it can be calculated that, under the premise of guaranteeing temperature uniformity, IC can reduce cooling time and improve production efficiency. By comparing the temperature fields of intermediate slabs of 40–110 mm under different process conditions, the changes of the theoretical value of production efficiency improvement under the condition of single-slab controlled rolling and multislab alternately controlled rolling are obtained. The production efficiencies of the single-slab IC and the multislab alternate IC are improved by 23–87% and 49.1–14.5%, respectively, where the single-slab IC means to

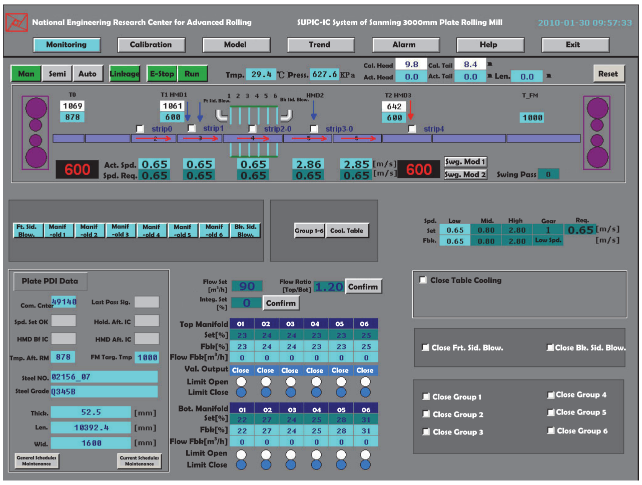


Figure 5: Home screen of HMI.

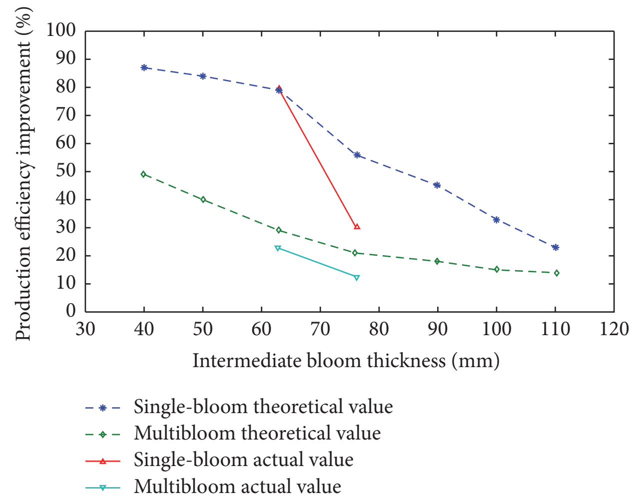


Figure 6: Comparison of the actual value and the theoretical value on production efficiency improvement of intermediate cooling.

cool plates one by one and the multislab alternate IC refers to the simultaneous cooling of a plurality of slabs.

The improvement value $\Delta\eta_{SS}$ of the production efficiency of the single-slab IC is derived from

$$\begin{aligned} \Delta\eta_{SS} &= \frac{t_S}{t_{AC}}, \\ t_S &= t_{AC} - t_{WC}, \\ t_{WC} &= t_{IC} + t_{RT}, \end{aligned} \tag{15}$$

where t_S is the saved time, t_{AC} is the air cooling time, t_{WC} is the water cooling time, t_{IC} is the intermediate cooling time, and t_{RT} is the rereddening time after IC.

The improvement value $\Delta\eta_{MS}$ of the production efficiency of the multislab alternate IC is derived from

$$\begin{aligned} \Delta\eta_{MS} &= \frac{t_S}{t_{AC}}, \\ t_S &= t_{AC} - t_{WC}, \\ t_{AC} &= \frac{t_{TAC}}{n} + t_{IN} * (n-1), \\ t_{WC} &= \frac{t_{TWC}}{n} + t_{IN} * (n-1) + t_{TN}, \end{aligned} \tag{16}$$

where t_S is the saved time of each plate, t_{AC} is the air cooling time of each plate, t_{WC} is the water cooling time of each plate, t_{TWC} is the total water cooling time, t_{IN} is the slab interval time, t_{TN} is the transport time, and n is the number of slabs.

In actual production, because of the operation reason or the logical limit of the control system, the production efficiency improved by IC is certainly not as high as the theoretical value. Compared with the conventional controlled rolling process, the IC process has higher production efficiency. Figure 6 shows that the production efficiencies of single-slab IC and multislab alternate IC are improved by up to 79.13% and 22.65%, respectively, for rolling thickness from 63 mm to 25 mm and by 30.36% and 12.67%, respectively, for rolling thickness from 76 mm to 46 mm. As can be seen, IC effectively improved the production efficiency of control rolling.

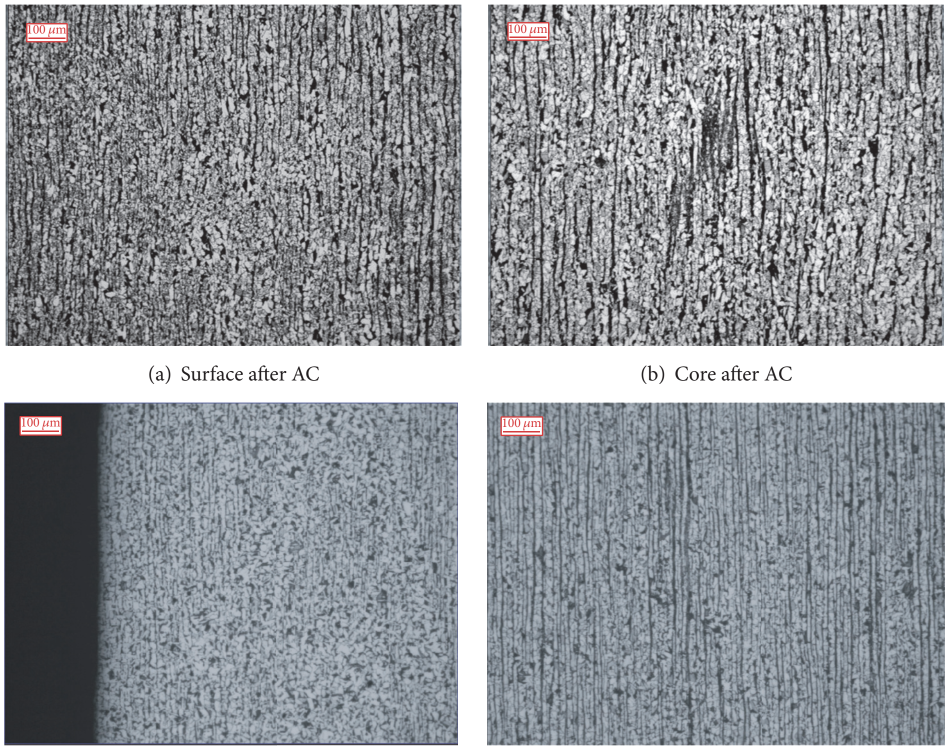
5.2. Mechanical Property Improvement. In order to investigate the differences of production mechanical properties between IC and conventional AC, we tested the effects of two different processes on the mechanical properties of the Q345B steel plate with the same specification. The mechanical properties of the steel plate are shown in Table 1. The results show that IC can effectively improve impact energy and yield strength but cannot significantly change the elongation. This is because IC inhibits the recrystallization grain growth and refines the austenite grains.

The microstructure at room temperature of Q345 steel produced by high efficiency controlled rolling process is shown in Figure 7. The surface microstructures of both sides and the center are fine ferrite and pearlite. And the ferrite grain size number at 1/4 thickness position of steel plate is 10.4–10.6. The core microstructure is even smaller and is accompanied by a small amount of banded structure. For Q345 steel which is produced by the conventional TMCP process, the ferrite grain size number at 1/4 thickness position is only 8.6–9.1.

5.3. Alloy Reduction Effect. Niobium (Nb) is an important microalloying element added in high-strength ship plate, and it can effectively improve the strength and toughness of the finished plate. But Nb is expensive, and high Nb content in the alloy leads to high cost. By using intermediate cooling, material composition optimization, and process parameters optimization, Nb content gradually reduces from an average of 200 ppm to about 120 ppm under the premise of ensuring the qualified and stable performance of high-strength ship plate. Thus, the goal of reducing cost and improving efficiency is achieved. The yield strength distribution of the steel plate before and after optimization is shown in Figure 8, from

Table 1: Optimized input-to-hidden layer weights.

Number	Rolling code	Grade	Thickness (mm)	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Cold bending	Impact energy (J)	Cooling mode
1	0926086	Q345B	16	375	555	28	Intact	147/128/113	IC
2	0922087	Q345B	16	385	540	29	Intact	151/164/146	IC
3	0922088	Q345B	16	390	545	30	Intact	159/134/173	IC
4	0922089	Q345B	16	345	535	29	Intact	102/72/72	AC
5	0922090	Q345B	16	350	525	32	Intact	119/92/92	AC



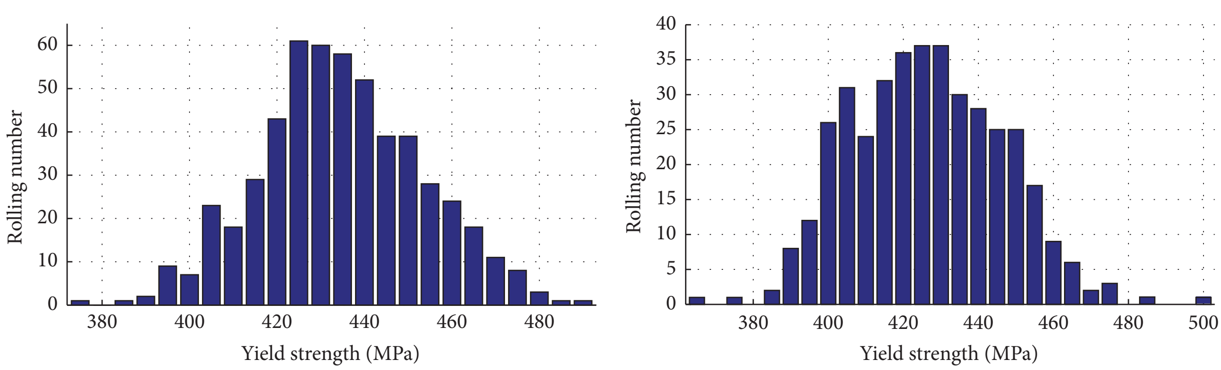
(a) Surface after AC

(b) Core after AC

(c) Surface after IC

(d) Core after IC

Figure 7: Microstructure of Q345 steel after AC and IC.



(a) High Nb alloy

(b) Low Nb alloy

Figure 8: Statistical histogram of yield strength of steel plate before and after optimization.

which it can be found that the peak interval is slightly increased and the fluctuation range is basically unchanged.

5.4. Alloy Reduction Effect. As shown in Figure 9, IC and AC are compared in terms of surface quality. It can be seen that intermediate cooling, which reduces the formation of secondary oxide scale on the plate surface and the chromatic aberration of the plate surface, greatly improves the surface quality of the steel plate. Because of lowering the surface temperature of the intermediate slab, intermediate cooling reduces the formation of Fe_2O_3-based secondary iron oxide scale, promotes the formation of FeO and Fe_3O_4, and converts FeO into uniform and dense oxide scale with strong adhesion composed of Fe_3O_4 + Fe at low temperature. Therefore, this kind of steel plate not only has smooth surface, but also has good resistance to atmospheric corrosion in the process of transportation and storage, which has been validated by experiments [15].

6. Conclusion

Based on the analysis on IC process and equipment, a cooling control scheme with combined feedforward, feedback, and adaptive algorithms is proposed. The IC control system

(a) Intermediate cooling

(b) Air cooling

Figure 9: Comparison of surface qualities of steel plates under different cooling conditions.

realizing uniform cooling effectively shortens the cooling time and improves the average controlled rolling efficiency by 17.66%.

The intermediate cooling can effectively inhibit the growth of austenite grain and improve the impact toughness and yield strength of Q345B steel plate. By using this mechanism, the alloy-reduced production of high-strength shipbuilding steel containing Nb and Q345B steel containing Als is carried out.

The formation of secondary oxide scale on the plate surface and the chromatic aberration of the plate surface are reduced and the surface quality of the steel plate is greatly improved.

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

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